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TWO-GROUP SRE FLUXES IN TWO DIMENSIONS

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TWO-GROUP SRE FLUXES IN TWO DIMENSIONS

By

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ABSTRACT

Several two-group diffusion problems, representing the Sodium Reactor Experiment, have been solved by means of NICK-2, a two-dimensional (r, z) multigroup diffusion code. The problems represented the following operational conditions:

1) Wet criticality - 33 elements loaded, and all components at a uniform temperature of 180°C.

2) Low temperature operation - 43 elements loaded, inlet coolant temperature 260°C (500°F), and outlet coolant temperature 343°C (650°F).

3) High temperature operation - 43 elements loaded, inlet coolant temperature 260°C (500°F), and outlet coolant temperature 516°C (960°F).

Two two-dimensional fluxes and power densities are given for the above cases. In addition, the results for reactivity and critical mass are compared with the results of the usual one-dimensional approximation, assuming separability of the fluxes in cylindrical coordinates. The close agreement obtained indicates that the one-dimensional approximation represents the two-dimensional situation quite well, even for high temperature operation.

I. INTRODUCTION

To gain insight into two-dimensional effects in a large cylindrical power reactor, a series of problems has been run, using NICK-2, a two-dimensional multigroup diffusion code. Two neutron energy groups were used and the dimensions and parameters were chosen to be representative of the SRE reactor. The purpose of this report is to make the results obtained available to all interested persons. The representative cases are described, the equations and group parameters are given, and all pertinent results are presented.

The two-dimensional character of the problem arises from two causes: the group parameters are functions of the local temperature, and the fluxes are not exactly separable into products of the form:

$$\phi(r, z) = \phi_R(r) \cdot \phi_Z(z) ,$$

where

ϕ = flux,

r = radius,

z = height.

If the temperature is constant, as in the wet critical case, or if average values are taken, the parameters become constants and an analytical solution can be obtained by assuming separability. Approximate solutions of this type have been obtained for the wet critical and the high temperature cases. It was found that the reactivity and critical mass were quite close to the values obtained by the more elaborate two-dimensional calculation. The fluxes and power densities obtained are, of course, not the same for the two different methods, but the differences are small enough to make the one-dimensional results adequate for all but the most exacting calculations.

II. CASES STUDIED

The three operating conditions studied were the following:

A. WET CRITICAL CASE

All components were assumed to be at a temperature of 180°C and a 33-element fuel loading was assumed. The results can be compared with the results of the critical experiment, as well as the results of the analytical one-dimensional solution. Both the two-dimensional and the approximate analytical solution indicate a critical loading of 33.2 elements. The experimental result was 32.6 elements. This close agreement gives the best available check on the accuracy of the parameters used in the equations.

B. LOW TEMPERATURE OPERATION

The reactor was assumed to be operating with coolant inlet and outlet temperatures of 260 and 343°C, respectively, and with 43 fuel elements loaded. Except for the fuel loading, these are the expected conditions for a preliminary period of operation at reduced power. Comparison with the experimental results will require a correction for the core size, but this case can be compared directly with the high temperature case. As expected, the asymmetry introduced by the small temperature gradient is very slight in this case.

C. HIGH TEMPERATURE OPERATION

The reactor was assumed to be operating with coolant inlet and outlet temperatures of 260 and 516°C, respectively, again with 43 elements loaded. These are the maximum design values for the outlet temperature and fuel loading. In addition to solving the equation in two dimensions, average values for the parameters were taken and the problem reduced to one dimension. Analytic solution of the resulting one-dimensional problem gave very close agreement with the two-dimensional solution for the reactivity, although in two dimensions the flux was markedly asymmetrical as well as nonseparable.

In all cases, no fuel burnup or fission product poisoning was assumed. The long term effects of these factors on the reactivity have been studied for the high temperature operating conditions and these results will be reported separately.

III. TWO-GROUP PARAMETERS

The two-group model used here requires the specification of six independent parameters at all points within the reactor region. If we write the two equations in the form:

$$\nabla \cdot \left(\frac{1}{3\Sigma_1} \nabla \phi_1 \right) - \Sigma_{sl} \phi_1 + \nu \epsilon \Sigma_f \phi_2 = 0 \qquad \ldots(1)$$

and

$$\nabla \cdot \left(\frac{1}{3\Sigma_2} \nabla \phi_2 \right) - \Sigma_a \phi_2 + p \Sigma_{sl} \phi_1 = 0 \, , \qquad \ldots(2)$$

then $\nu = 2.46$ and $\epsilon = 1.043$ (in this particular case) are constants and the six parameters are:

Σ_1 = fast transport cross section,

Σ_2 = thermal transport cross section,

Σ_{sl} = slowing down cross section,

Σ_a = thermal absorption cross section,

p = resonance escape probability,

Σ_f = thermal fission cross section.

The reactor was divided into four regions:

<u>The Core</u>:

Height = 183 cm;

Radius = 84.8 cm (33 elements)

= 96.8 cm (43 elements)

<u>The Bottom Reflector</u>:

Height = 61 cm;

Radius = core radius

<u>The Top Reflector</u>:

Height = 61 cm;

Radius = core radius

<u>The Side Reflector</u>:

Height = 305 cm;

Inner radius = core radius

Outer radius = 156.4 cm

Within each region, the six parameters were assumed to be linear functions of z only. The range of z in the top and bottom reflectors is so small that the parameters were assumed constant in these regions. The additional assumption was made that p differs from unity only in the core region, i.e., that epithermal captures are of importance only in the fuel. In calculating p, allowance was made for the fact that the fuel temperature is higher than the coolant temperature during power operation.

Table I gives the values used for the parameters. In each variable region, values at the upper and lower boundaries are given. Values at intermediate points were obtained by linear interpolation. In the wet critical case, of course, the values are constant within each region and the same for the bottom and top reflectors.

TABLE I

TWO-GROUP PARAMETERS FOR SRE

	Σ_1 (cm^{-1})	Σ_2 (cm^{-1})	Σ_{sl} (cm^{-1})	Σ_a (cm^{-1})	Σ_f (cm^{-1})	p
Wet Critical (180°C)						
Core	0.31580	0.34980	0.00284	0.00600	0.00357	0.8380
Bottom and Top Reflectors	0.30600	0.34700	0.00295	0.00177	0	1.00
Side Reflector	0.33200	0.36100	0.00310	0.000512	0	1.00
Low Temperature (260 - 343°C)						
Core: bottom	0.31430	0.34790	0.00286	0.00583	0.00351	0.8346
top	0.31330	0.34670	0.00287	0.00570	0.00345	0.8338
Bottom Reflector	0.30470	0.34560	0.00296	0.00162	0	1.00
Top Reflector	0.30370	0.34440	0.00297	0.00152	0	1.00
Side Reflector:						
bottom	0.33060	0.35950	0.00311	0.000472	0	1.00
top	0.32940	0.35820	0.00312	0.000439	0	1.00
High Temperature (260 - 516°C)						
Core: bottom	0.31420	0.34780	0.00286	0.00581	0.00350	0.8350
top	0.31110	0.34380	0.00289	0.00538	0.00330	0.8318
Bottom Reflector	0.30460	0.34550	0.00296	0.00161	0	1.00
Top Reflector	0.30160	0.34210	0.00299	0.00135	0	1.00
Side Reflector:						
bottom	0.33060	0.35950	0.00311	0.000472	0	1.00
top	0.32710	0.35560	0.00314	0.000389	0	1.00

The number of figures given is not an indication of the accuracy of the numbers; but is merely the number of figures carried in the computations, in order to represent the variations in the parameters as functions of temperature and position.

The parameters for the one-dimensional calculations were obtained from the values in Table I. For the high temperature case, average values of the upper and lower quantities were taken for each region. The effective core height (height of core plus reflector savings) was taken to be 247.7 cm in both cases. The other values used are listed in Table II.

TABLE II

PARAMETERS FOR TWO-GROUP RADIAL CALCULATION

Parameter		Wet Critical	High Temperature (average values)
$D_1 = \frac{1}{3\Sigma_1}$:	Core	1.056	1.0662
	Reflector	1.004	1.0136
$D_2 = \frac{1}{3\Sigma_2}$:	Core	0.9529	0.96395
	Reflector	0.9234	0.93227
$\tau = \frac{1}{3\Sigma_1\Sigma_{sl}}$:	Core	372	370.84
	Reflector	324	324.36
$L^2 = \frac{1}{3\Sigma_2\Sigma_a}$:	Core	158.8	172.29
	Reflector	1803	2165.6
p :	Core	0.8378	0.8334
	Reflector	1.0000	1.0000
$k = \frac{\Sigma_f}{\Sigma_a} \nu \epsilon p$:	Core	1.281	1.3015
	Reflector	0.000	0.0000

D_1 = fast diffusion coefficient (cm)
D_2 = thermal diffusion coefficient (cm)
τ = age of thermal neutrons (cm^2)
L^2 = thermal migration area (cm^2)
p = resonance escape probability
k = infinite multiplication factor

IV. RESULTS

The results for the reactivity in the three cases are listed in Table III, for both the one dimensional and two dimensional methods of computation.

TABLE III

COMPARISON OF RESULTS FROM ONE- AND TWO-DIMENSIONAL COMPUTATIONS

	Calculated Reactivity, k_{eff}	
	One-dimensional	Two-dimensional
Wet critical (33 fuel elements)	0.9993	0.9989
Low temperature (43 fuel elements)	1.0347	1.0338
High temperature (43 fuel elements)	1.0397	1.0400

These results show complete agreement between the two methods, within the limits of errors. The errors in the one-dimensional calculations of k_{eff} are of order $\pm 5 \times 10^{-4}$, or 5 parts in the last place given in Table III. For NICK-2, the errors are more difficult to estimate, because of the dependence of mesh spacing and other factors; but the uncertainties in k_{eff} should not exceed ± 2 parts in the last place given. It should be emphasized that these errors are due to the inexactness of the solutions obtained to the mathematical problems solved by the respective computing machine programs. The input data were identical for the two methods, but the techniques of solution are quite different.

The two-dimensional thermal fluxes and fission densities are illustrated in Figures 1 to 5, which list the values at selected mesh points within the reactor. The coordinates of each point are given at the top of each column (r coordinate) and to the left of each row (z coordinate). The quantities are all normalized to unity at the center of the core. The fission density for the wet critical case has the same shape as the thermal flux. Therefore, no plot of this quantity is necessary.

The figures show that the fluxes and fission densities are not separable functions of r and z, even in the wet critical case where they are, of course, symmetric about the midplane ($z = 0$). The nonsymmetry of these quantities in the nonuniform temperature cases is also apparent. These effects are not large, however, even in the high temperature case. The maximum amount by which the fission densities differ from the separable, symmetric solution is less than 5% in all cases. The maximum differences occur near the "corners" of the core, as expected, and result chiefly from the nonseparability, rather than from the nonsymmetry of the problem.

The thermal fluxes exhibit somewhat greater deviations from symmetry and separability. In general, however, the accuracy of any two-group calculation would not be sufficient to warrant use of the two-dimensional solution for more "accurate" flux values.

V. SUMMARY AND CONCLUSIONS

The agreement between the one-dimensional approximation and the much more elaborate two-dimensional calculation of reactivity is excellent. These calculations therefore give a useful check on the reliability of the analytical methods commonly used to solve the reactor equations.

Although only slight changes from the existing data were observed, the fluxes and fission densities resulting from the NICK-2 calculation may be of interest in many applications. For example, these results have been used to compute long-term reactivity changes. Successive calculations of fluxes and reactivity, with changes in the various parameters due to burnup and fission product poisoning, can be accomplished more easily by the two-dimensional method, since the parameters will become two-dimensional functions of position.

Although the methods of accounting for the changes in parameters with temperature and position were very rough approximations, the results should indicate the asymmetries introduced by these variations quite well.

RADIUS (CM)

HEIGHT (CM)		AXIS 0.0	19.1	31.9	44.7	63.8	CORE RADIUS 81.8	87.8	105.8	156.4
	152.5	0.015	0.015	0.014	0.013	0.011	0.010	0.010	0.008	0.0003
	120.5	0.288	0.280	0.266	0.246	0.212	0.186	0.181	0.143	0.0046
TOP OF CORE	94.5	0.526	0.510	0.484	0.447	0.383	0.347	0.351	0.283	0.0088
	88.5	0.520	0.505	0.479	0.442	0.379	0.357	0.383	0.318	0.0098
	70.5	0.637	0.618	0.586	0.541	0.464	0.451	0.499	0.423	0.0129
	52.5	0.786	0.763	0.723	0.666	0.571	0.554	0.614	0.519	0.0157
	37.5	0.888	0.862	0.816	0.752	0.644	0.624	0.692	0.583	0.0175
	15.0	0.982	0.952	0.902	0.831	0.711	0.689	0.763	0.642	0.0193
MIDPLANE	0.0	1.000	0.970	0.919	0.847	0.725	0.702	0.777	0.654	0.0196
	−15.0	0.982	0.952	0.902	0.831	0.711	0.689	0.763	0.642	0.0193
	−37.5	0.888	0.862	0.816	0.752	0.644	0.624	0.692	0.583	0.0175
	−52.5	0.786	0.763	0.723	0.666	0.571	0.554	0.614	0.519	0.0157
	−70.5	0.637	0.618	0.586	0.541	0.464	0.451	0.499	0.423	0.0129
	−88.5	0.520	0.505	0.479	0.442	0.379	0.357	0.383	0.318	0.0098
CORE BOTTOM	−94.5	0.526	0.510	0.484	0.447	0.383	0.347	0.351	0.283	0.0088
	−120.5	0.288	0.280	0.266	0.246	0.212	0.186	0.181	0.143	0.0046
	−152.5	0.015	0.015	0.014	0.013	0.011	0.010	0.010	0.008	0.0003

Figure 1. Thermal Flux - Wet Critical

RADIUS (CM)

	HEIGHT (CM)	AXIS 0.0	19.1	38.3	57.4	75.8	CORE RADIUS 93.8	99.8	124.8	156.4
	152.5	0.017	0.017	0.015	0.014	0.012	0.010	0.009	0.006	0.0003
	120.5	0.314	0.306	0.283	0.249	0.211	0.179	0.171	0.104	0.0057
	94.5	0.549	0.535	0.496	0.435	0.368	0.324	0.322	0.204	0.0111
TOP OF CORE										
	88.5	0.539	0.526	0.487	0.427	0.362	0.331	0.350	0.229	0.0124
	70.5	0.648	0.632	0.584	0.512	0.435	0.413	0.451	0.303	0.0164
	52.5	0.793	0.773	0.715	0.626	0.531	0.504	0.552	0.371	0.0199
	37.5	0.893	0.870	0.805	0.704	0.597	0.567	0.620	0.416	0.0223
	15.0	0.983	0.959	0.886	0.776	0.658	0.623	0.682	0.457	0.0245
MIDPLANE	0.0	1.000	0.975	0.901	0.789	0.668	0.634	0.694	0.465	0.0250
	−15.0	0.980	0.956	0.884	0.773	0.655	0.622	0.681	0.457	0.0245
	−37.5	0.885	0.863	0.798	0.699	0.593	0.563	0.617	0.414	0.0223
	−52.5	0.784	0.764	0.707	0.619	0.525	0.500	0.548	0.369	0.0199
	−70.5	0.637	0.621	0.575	0.503	0.428	0.407	0.447	0.301	0.0163
	−88.5	0.526	0.513	0.475	0.416	0.353	0.325	0.345	0.227	0.0123
CORE BOTTOM										
	−94.5	0.535	0.521	0.482	0.423	0.358	0.317	0.317	0.202	0.0110
	−120.5	0.301	0.294	0.272	0.239	0.203	0.173	0.167	0.103	0.0057
	−152.5	0.016	0.016	0.015	0.013	0.011	0.009	0.009	0.006	0.0003

Figure 2. Thermal Flux - Low Temperature Operation

RADIUS (CM)

HEIGHT (CM)	0.0	19.1	38.3	57.4	75.8	93.8
88.5	0.535	0.521	0.483	0.423	0.359	0.328
70.5	0.643	0.627	0.580	0.509	0.432	0.410
52.5	0.789	0.769	0.711	0.623	0.529	0.502
37.5	0.889	0.867	0.802	0.702	0.595	0.565
15.0	0.982	0.957	0.885	0.774	0.657	0.622
0.0	1.000	0.975	0.901	0.789	0.668	0.634
−15.0	0.982	0.957	0.885	0.774	0.656	0.623
−37.5	0.889	0.866	0.801	0.701	0.595	0.565
−52.5	0.788	0.768	0.710	0.622	0.528	0.502
−70.5	0.641	0.625	0.578	0.507	0.431	0.410
−88.5	0.530	0.517	0.479	0.420	0.356	0.327

Figure 3. Fission Density - Low Temperature Operation

RADIUS (CM)

HEIGHT (CM)		AXIS 0.0	19.1	38.3	57.4	75.8	CORE RADIUS 93.8	99.8	124.8	156.4
	152.5	0.018	0.018	0.017	0.015	0.012	0.010	0.010	0.006	0.0003
	120.5	0.330	0.322	0.298	0.262	0.222	0.186	0.177	0.107	0.0059
TOP OF CORE	94.5	0.567	0.553	0.572	0.449	0.380	0.333	0.329	0.207	0.0113
	88.5	0.557	0.543	0.503	0.441	0.374	0.340	0.357	0.232	0.0126
	70.5	0.662	0.646	0.597	0.524	0.445	0.420	0.456	0.305	0.0166
	52.5	0.805	0.784	0.725	0.635	0.539	0.510	0.555	0.372	0.0201
	37.5	0.902	0.879	0.813	0.711	0.604	0.571	0.622	0.416	0.0225
	15.0	0.987	0.962	0.890	0.778	0.660	0.625	0.681	0.456	0.0247
MIDPLANE	0.0	1.000	0.975	0.901	0.788	0.668	0.633	0.691	0.464	0.0251
	−15.0	0.977	0.952	0.880	0.770	0.653	0.619	0.677	0.455	0.0246
	−37.5	0.877	0.855	0.790	0.692	0.587	0.558	0.611	0.412	0.0223
	−52.5	0.774	0.754	0.697	0.610	0.518	0.494	0.542	0.367	0.0199
	−70.5	0.626	0.610	0.564	0.494	0.420	0.401	0.441	0.299	0.0163
CORE BOTTOM	−88.5	0.514	0.501	0.464	0.407	0.346	0.319	0.340	0.225	0.0123
	−94.5	0.522	0.509	0.471	0.413	0.350	0.311	0.312	0.201	0.0110
	−120.5	0.294	0.287	0.266	0.234	0.199	0.170	0.164	0.102	0.0057
	−152.5	0.016	0.015	0.014	0.013	0.011	0.009	0.009	0.006	0.0003

Figure 4. Thermal Flux - High Temperature Operation

RADIUS (CM)

HEIGHT (CM)	0.0	19.1	38.3	57.4	75.8	93.8
88.5	0.541	0.528	0.488	0.428	0.363	0.330
70.5	0.647	0.631	0.584	0.512	0.435	0.411
52.5	0.791	0.771	0.713	0.625	0.530	0.502
37.5	0.891	0.868	0.803	0.703	0.596	0.564
15.0	0.982	0.957	0.885	0.775	0.657	0.622
0.0	1.000	0.975	0.901	0.788	0.668	0.633
−15.0	0.982	0.957	0.884	0.773	0.656	0.622
−37.5	0.888	0.865	0.800	0.700	0.594	0.565
−52.5	0.787	0.767	0.709	0.620	0.527	0.502
−70.5	0.640	0.624	0.577	0.505	0.430	0.410
−88.5	0.529	0.515	0.477	0.418	0.355	0.328

Figure 5. Fission Density - High Temperature Operation